On the Angular Radiance Closure of Tropical Cumulus Congestus Clouds

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1. Introduction

Tropical cumulus congestus clouds arguably manifest the most significant three-dimensional radiative transfer (3D RT) impacts apparent within Nature. The contribution of net horizontal photon transport to the top-of-atmosphere albedo (*i.e.*, the discrepancy from plane-parallel results) is poorly known for this cloud type. 3D RT simulations relying on cloud-resolving-model output arrive at different conclusions dictated by uncertain ice microphysical model parameterizations. Data-driven studies are few, reflecting the difficulties of performing the initial cloud property retrievals for these complex clouds.

Data-driven simulations are important in part because they can help assess the realism of modelled cloud representations. Satellite data can provide a realistic spatial representation, and multi-angle-viewing satellite instruments such as MISR make possible an assessment of any fully three-dimensionally reconstructed cloud. If the multi-view measured radiances can be accurately simulated, the radiative behavior of the cloud has been reconstructed with a degree of confidence not available from single-view instruments. The climatic impact of such clouds can then be assessed with great confidence.

This research evaluates the suitability of cumulus congestus clouds reconstructed from MISR imagery for 3DRT studies. Three cloud cases were selected that showed a large degree of structure, had minimal upper-level cirrus, and contained some high optical depths. The cloud heights were operationally recnstructed from the MISR satellite imagery, while the optical depths were retrieved by applying plane-parallel theory to the nadir reflectances, at a solar zenith angle of 20 degrees. For most simulations a vertical resolution of 250 m is applied. The spatial resolution is 275 m.

Four different assumptions or parameters were used to construct the vertical dimension:

* a column vertical-mean volume extinction coefficient (the reference case)
* a volume extinction coefficient increasing as the two-thirds power of height (the adiabatic assumption)
* a volume extinction coefficient increasing as the two-thirds power of height, at a 25 m vertical resolution
* an optical depth retrieved from reflectances averaged over a 2.2 km*km area

2. Cloud input field

Active convection occurs even at the normally convectively-quiescent time of the 10:30 AM local time orbit near tropical landmasses with coastal mountain ranges. The selected scene is slightly north of Papua New Guinea, occurring on Sept. 30, 2001.

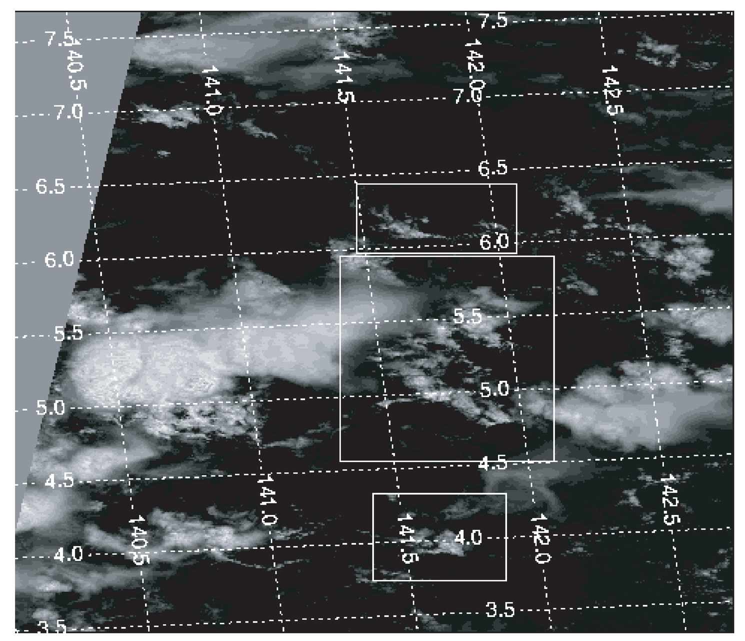

Fig. 1: MISR nadir reflectances, orbit 9490 path 101. Latitudes and longitudes are indicated by the white dashed lines.

Three cases were selected from the western side of the orbit, where specular reflection ("sun glint") is less pronounced. The cases are outlined by the white boxes shown in Fig. 1 and 2. The northern-most case is case "1", the middle case, case "2", and the southern-most case, case "3".

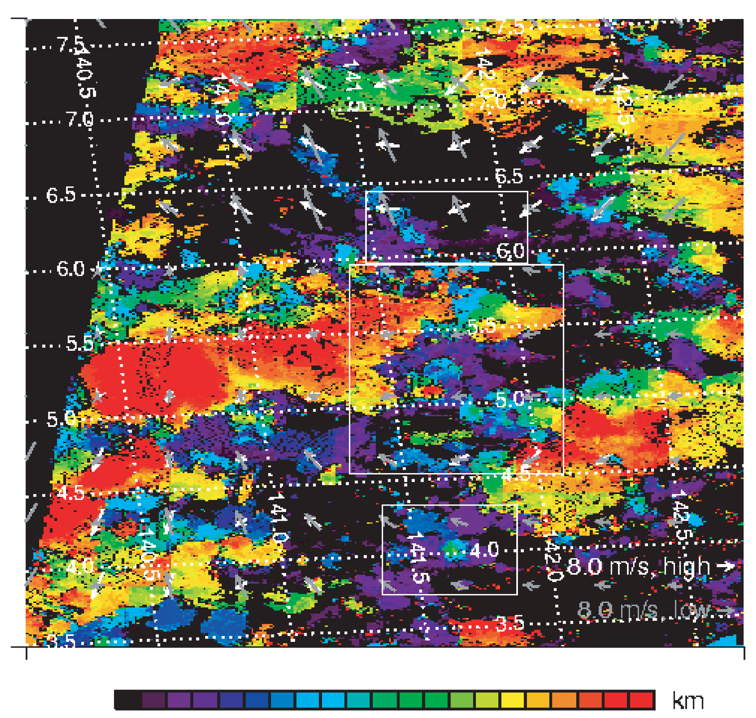

Fig. 2: The operationally-derived stereo cloud heights and winds

3. Comparison to NCEP and MODIS

A comparison of the MISR winds to the National Center for Environmental Prediction (NCEP) winds reveals that the MISR wind retrieval is not perceiving the upper-level strong westward winds and is mostly responding to the eastward cloud movement of clouds below 400 mb (~7.5 km). Both the southward movement of clouds above 750 mb (~ 3 km) and the northward movement of lower clouds are identified by the MISR stereoimaging retrieval

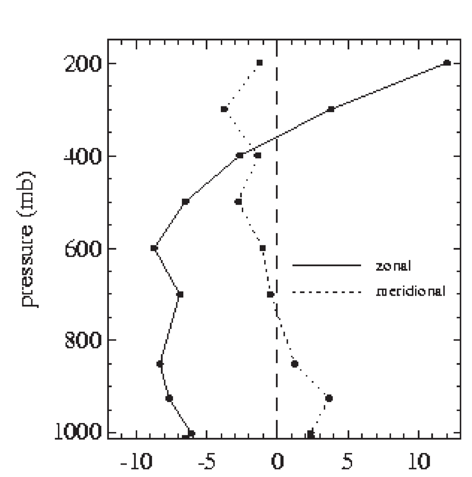

Fig. 3: The daily-average National Center for Environmental Predication Reanalysis winds for 141.25E, 5N on Sept. 30,2001

A comparison is done to the MODIS cloud top heights. The MODIS cloud top heights are retrieved by applying the mean TOGA Coupled Ocean-Atmosphere Response Experiment sounding to the MODIS cloud top temperatures. The correspondence is generally good, with MISR cloud top heights somewhat lower than those for MODIS. The largest discrepancies occur where MODIS senses upper-level clouds and MISR responds to an optically-thicker lower layer. In a further breakdown by optical depth, for the low optical depth clouds (usually upper-level cirrus) MISR places the cloud tops higher than MODIS. One explanation is that MISR is using a wind more appropriate to a lower altitude for the dual wind/height retrieval of these cases.

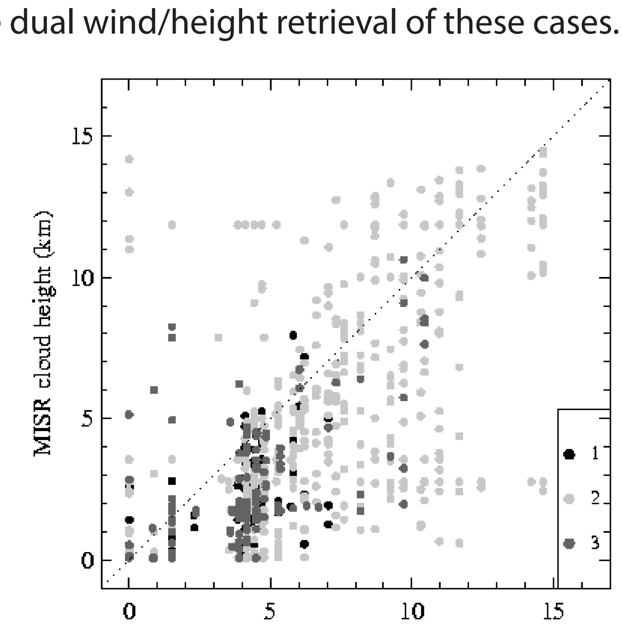

Fig. 4: MISR versus MODIS cloud heights for the three cases. MISR heights are averaged to match the MODIS 5 km resolution

4. Optical Depth Retrieval

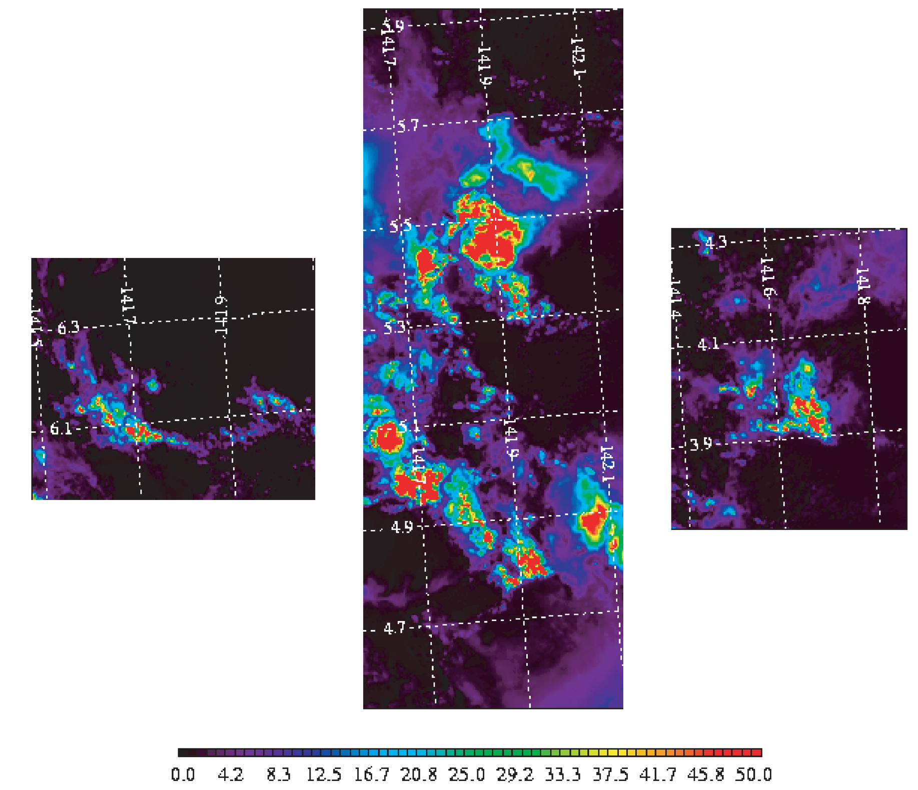

Fig. 5: Plane-parallel optical depths for the three cases. The radiative transfer model "Streamer" was used, with a surface albedo of 0.043, Rayleigh scattering included, and no gaseous absorption or aerosols. These choices reflect consistency between Streamer, the MISR measurements, and the subsequent Monte Carlo calculations. The code was modified to incorporate Mie scattering. Clouds with cloud top heights at 5.5 km or below are assumed to be composed entirely of liquid drops with an effective radius of 10 micron, clouds with tops above 11 km are assumed to be composed entirely of spherical ice particles with an effective radius of 30 microns, and clouds with tops in between 5.5 and 11 km are treated as mixed-phase, with ice and liquid proportions established as a linear function of cloud top height. For case 1 and 3, most of the cloud is liquid (because their cloud top heights are at about the freezing level).

5. Clear-sky Characteristics and Modeling

The analytical clear-sky reflectance model of Breon (1993) was coded up and a best fit sought to the clear-sky measurements. The Breon model accounts for ocean specular reflectance, first and second-order molecular scattering, specular reflectance combined with molecular scattering. The ocean glitter pattern dependence upon wind speed and direction is modeled using Cox and Munk (1954). Clear-sky regions were identified by both the MISR and MODIS nadir-view radiometric cloud mask, and further delineated by examining all nine camera views for areas with high spatial homogeneity and maximum radiance values.

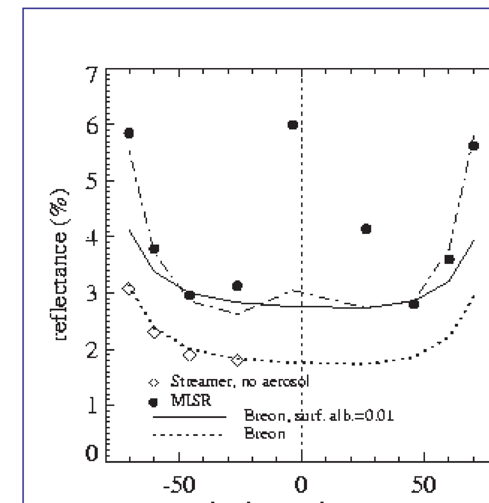

Fig. 6: Mean observed clear-sky reflectances (solid circles), the full Rayleigh scattering contribution calculated by Streamer (open diamonds), the Breon model 1st and 2nd order Rayleigh contribution without a surface albedo (dotted line) and with a surface albedo of 0.01 (solid line). MISR values are corrected to account for gaseous absorption. (The dot-dash line also includes a simple aerosol model; this was not used with the Monte Carlo model however).

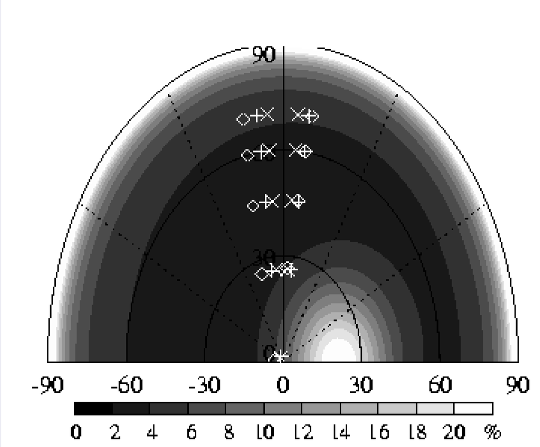

Fig. 7: The Breon-modeled clear-sky reflectance as a function of viewing zenith angle (radial variable) and relative azimuth angle (angular variable). The solar zenith angle is 20 degrees. White diamonds, plus signs, and crosses indicate the viewing angles of the MISR cameras for the three cases.

6. Monte Carlo reflectance simulations

For all simulations the cloud base is at 500 m and a minimum extinction of 0.25 /km is imposed. The forward Monte Carlo (Davies, 1978) uses the Breon (1993) model as a lower boundary, and Mie scattering was implemented. Most runs are done with 10^7 photons, yielding domain-averaged reflectances accurate to 1%.

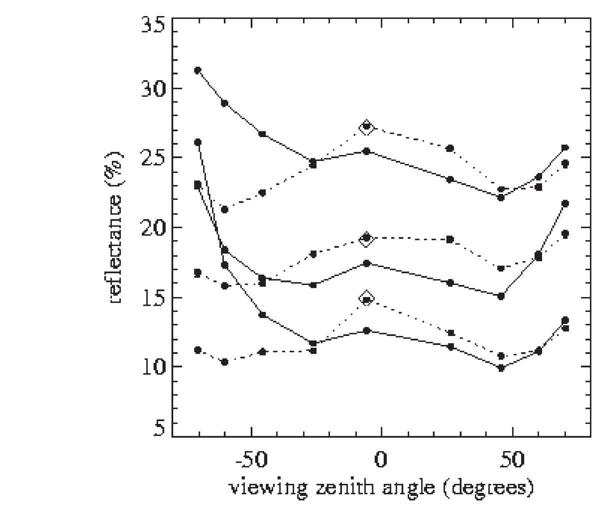

Fig. 8: Comparison of Monte Carlo reflectances (dotted line) to observed values (solid line) for the three cases (nadir Monte Carlo independent pixel reflectances are shown as open diamonds).

The salient feature of Fig. 8 is the poor correspondence between the Monte Carlo simulations and the observations. The simulated near-nadir reflectances exceed the observations and the simulated reflectances at the oblique angles are usually less than what is observed. Not enough variation with viewing angle is captured by the simulations.

Fig. 9 shows the results of further Monte Carlo experiments using other assumptions or parameters for constructing the vertical cloud dimension, for case 3 only. The arguably best simulation occurs when a vertically-increasing volume extinction coeffficient is used at a vertical resolution of 25 m (solid line with asterisks); this simulation shows more variation with viewing angle than any other simulation.

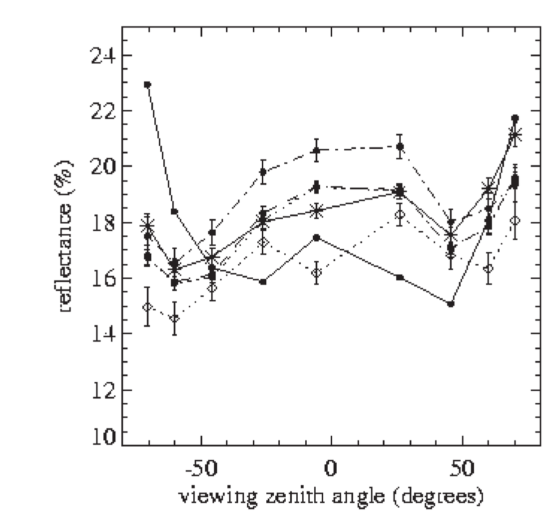

Fig. 9: Monte Carlo domain-mean reflectances using vertical-mean extinction coefficients at 250 m vertical resolution (dotted line with filled circles), a vertically-increasing extinction coefficients at 250 m vertical resolution (dashed line with filled circles; mostly lies on top of the reference case), and at 25 m vertical resolution (solid line with asterisks). A simulation using optical depths retrieved from 2.2 km^2-averaged reflectances is also shown (dot-dash line with filled circles).

7. Concluding Remarks

Monte Carlo simulations of tropical cumulus congestus clouds reconstructed in three dimensions from MISR imagery compare poorly to the observed reflectances. This cals into doubt subsequent 3DRT studies on the impact of net horizontal photon transport on the albedo. The cause is thought to be optical and spatial cloud variability at scales not resolved by MISR, *i.e.* at scales less than ~ 250 m. Support for this explanation and a more complete description of this research can be found in a manuscript currently being prepared for submission to a journal, available through http://www.etl.noaa.gov/~pzuidema later this month.